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ABSTRACT

Brief Summary: This report details the research supported by a one-year grant from the Guest Investigator Program for the Solar Maximum Mission (SMM). The objectives of the study were to (i) perform comparative studies of hard X-ray emissions obtained from HXRBS on SMM with microwave data from the Very Large Array (VLA) and the frequency agile interferometer at Owens Valley Radio Observatory (OVRO) to investigate the processes driving the acceleration of electrons and ions during flares and (ii) compare the observations with predictions from new modelling efforts in order to identify signatures of the dominant processes.

Progress and Accomplishments: Significant results are reported in three papers submitted to journals, two contributed papers submitted to a conference proceedings and two contributed papers at national conferences (see below). In addition, the PI's were organizers of a Max'91/SMM workshop which focussed on coordinated solar flare observations, of which data from SMM played a crucial role.

The research involved (i) case studies of five flares showing the development of broken-power spectra in association with Doppler shifts in soft X-ray line emissions, indicating that quasi-static fields are important in determining the electron and ion dynamics, (ii) development of a simulation model detailing the processes suggested by the above observations, (iii) completion of a statistical study of 93, impulsive, hard X-ray flares, which shows that the development of a broken-power law spectrum described above is very common; a new phenomeno was discovered as well, a *high energy lag* during the rise phase of impulsive flares, and (iv) multiwavelength comparison of two limb flares observed during the first Max'91 campaign.

Summary Bibliography:

<u>Papers Submitted or In Press</u>:

1. Interrelation of Soft and Hard X-Ray Emissions During Solar Flares I. Observations, 1991, R. M. Winglee, A. L. Kiplinger, D. M. Zarro, G. A. Dulk, and J. R. Lemen *Ap. J.*, in press.

2. Interrelation of Soft and Hard X-Ray Emissions During Solar Flares II. Simulation Model, 1990, R. M. Winglee, G. A. Dulk, P. L. Bornmann and J. C. Brown, *Ap. J.*, in press.

3. Characteristics of Hard X-ray Spectra of Impulsive Solar Flares, 1991, G. A. Dulk, A. L. Kiplinger and R. M. Winglee, *Ap. J.*, submitted.

4. Flare Dynamics in the Presence of Filamented Currents and Quasi-Static Fields: Implications for Microwaves and Soft and Hard X-Ray Emissions, R. M. Winglee, Workshop on Max'91/SMM Solar Flares: Observations and Theory, Estes Park, June 3–7, 1990, in press.

5. Observations of Two Solar Flares on June 20, 1989, T. A. Kucèra, G. A. Dulk, A. L. Kiplinger, T. S. Bastian and D. E. Gary, Workshop on Max'91/SMM Solar Flares: Observations and Theory, Estes Park, June 3–7, 1990, in press.

Contributed Talks

Simultaneous Hard and Soft X-Ray Observations of Impulsive Flares : Evidence for Acceleraction by Quasi-Static Electric Fields, R. M. Winglee, A. L. Kiplinger, G. A. Dulk, D. M. Zarro and J. R. Lemen, 176th Meeting of the American Astronomical Society, Albuquerque, June 10–14, 1990.

Observations of Two Large Off Limb Solar Flares in the Radio, X-rays and Hα, T. A Kucera, G. A. Dulk, R. M. Winglee, A. L. Kiplinger, T. S. Bastian and D. E. Gary, 21st Solar Physics Division Meeting, April 9–11, 1991.

Proceedings Published:

Third Max '91 Workshop - Max '91/SMM Solar Flares: Observations and Theory, Estes Park, June 3 – 7, 1990, edited by R. M. Winglee and A. L. Kiplinger.

PROGRESS REPORT

1. Cases Studies of the Soft and Hard X-Ray from Five Flares

The first part of our research (paper 1) utilized simultaneous observations of hard X-rays and soft X-ray line emissions at high time resolution ($\simeq$ 6 sec) from SMM to investigate the characteristics of the electron and ion acceleration during impulsive flares, and the relation, if any, among the processes driving this acceleration. The study involves five flares – three disk and two limb flares. Positional information is important in understanding the soft X-ray line emissions since the Doppler shift is dependent on the line-of-sight to the flare.

It was shown that for all the flares, the hard X-rays have a power-law spectrum that breaks-down during the rise phase and beginning of the decay phase. This type of spectrum is attributed to acceleration of electrons by quasi-static fields with the total potential drop being proportional to the break energy. Our results show that it is a common occurrence in impulsive flares. About half-way through the decay phase, the spectrum changes to either a single-power law or a power law which breaks up at high energies, possibly signifying the end of the driving electric field.

Further evidence that quasi-static fields are playing an important role in the particle acceleration comes from correlating the above features seen in hard X-rays with those in the soft X-ray line emissions. For the three disk flares, the line emissions show a blue-shifted component (due to the upward acceleration of ions into the corona) with the maximum inferred velocity reaching its peak value during the decay phase just at the time when the break in the X-ray spectrum vanishes. For limb flares, the soft X-ray line emissions show only a non-thermally broadened stationary component (arising from acceleration and heating perpendicular to the magnetic field); this broadening reaches a maximum at the hard ($\gtrsim$ 50 keV) X-ray peak rather than during the decay phase.

These observations are inconsistent with chromospheric evaporation (i.e., the explosive heating of the chromosphere) since both the blue shifts and the broadening are predicted to have the same dependence on the hard X-ray flux. On the other hand, acceleration via small scale quasi-static electric fields are expected to produce the above association between soft and hard X-ray features. In particular, such electric fields can readily produce the electron acceleration required to account for the observed broken power-law spectrum. This same electric field acts on the ions at the same time, producing the correlation between the electron and ion acceleration. In the presence of such small scale structures, the ions are first accelerated across the field lines and then up into the corona. This difference in acceleration, which is due to the difference in scale lengths along and across the field lines, is proposed as the source of the delay (relative to the hard X-ray peak) in the appearance of the largest blue-shifts seen in disk flares and the early appearance of strong broadening seen in limb flares.

2. Simulation Model

In order to test the above model, we performed two-dimensional (three velocity) electrostatic particle simulations (paper 2) which allows the investigation of the development of quasi-static fields self-consistently with the induced currents and particle acceleration. In the model, the particle acceleration is initiated by cross-field currents in the corona which are associated with the decay of current sheets high in the corona. These same current sheets are essential to reconnection models of solar flares. Because of the limited cross-field mobility of particles in a collisionless plasma, this cross-field current can only be closed in the chromosphere where cross-field transport is aided by collisions. As a result, strong quasi-static electric fields are set up which produce strong downward acceleration of electrons in the primary current region. On adjacent field lines, electrons are accelerated up into the corona to provide a return current but due to the relatively large cross-section of the return-current region, the electrons in this region remain relatively low in energy. The induced perpendicular currents are initially provided by the ions but as the chromosphere becomes heated by precipitation of energetic electrons, perpendicular electron currents become important. These electron currents in turn modify the particle acceleration in the latter part of the flare.

The calculated properties of the soft and hard X-ray and microwave emissions from such a system have the following properties: (i) acceleration by quasi-static electric fields and heating via wave-particle interactions produces electron distributions with a broken-power law, similar to those inferred from hard X-ray spectra; (ii) heating of the ambient plasma gives rise to a region of hot plasma which propagates down to the chromosphere at about the ion sound speed; (iii) the arrival of this hot plasma region in the chromosphere causes the hard X-ray flux to peak due to modification of the cross-field conductivity so that the passage of soft X-ray fronts and the hard X-ray peak are expected to be correlated; (iv) the perpendicular heating of coronal electrons is relatively slow and this can give rise to the observed delay of the microwave peak relative to the hard X-ray peak; (v) heavy ions are preferentially accelerated across the fields as the cross-field currents form, leading to enhancements of heavy ion abundances in the primary-current region. This enhanced heavy ion abundance may account for those inferred from soft X-ray line emissions; (vi) the ions in the primary current region are then accelerated upward by the same electric fields that accelerate the hard X-ray electrons downward and (vii) this parallel and perpendicular acceleration can give rise to Doppler shifts in soft X-ray line emissions similar to those seen during disk and limb flares.

The simulation model was extended in paper 4 to investigate the properties of the flare emissions as a function of the rise time of the flare. It was shown that the strongest blue-shifted components in the soft X-ray emissions and the longest microwave delays are expected when the rise time is long compared with the transit time of 100 eV electrons (i.e., much longer than several seconds). For flares with shorter rise times the blue-shift and the microwave delay become relatively weak, although strong broadening of the soft X-ray line emission is still expected.

3. A Statisical Study

The above results show that quasi-static fields may be common in impulsive flares. A statistical study (paper 3) was undertaken in order to quantify exactly how common these processes are. In performing this study, we obtained additional evidence for acceleration via quasi-static fields. This statistical study involved 93, impulsive, hard X-ray flares (174 burst peaks) that were observed by the HXRBS instrument on the SMM spacecraft. Our major findings are: (1) During the initial few seconds after the onset of rapidly rising bursts (i.e. rise times $\lesssim 5$ s, there is a "high-energy delay", where the rise in flux at energies $\gtrsim 150$ keV is delayed by a few seconds relative to that at energies $\lesssim 100$ keV. This high-energy delay is predicted by the simulation model and arises from the fact that, while electrons low in the corona experience only a small fraction of the total potential drop, they only have a relatively short distance to travel and hence arrive in the chromosphere before the high energy electrons that start higher in the corona. (2) At the times of peak flux, the power-law spectra almost always "break down" at an energy of about 100 keV. There is little or no dependence of break energy on the hard X-ray flux. (3) During the decay phase of bursts, the broken-down spectra usually change to either a single power-law or to one that is breaks up. The break energy of the broken-up spectra is usually lower after the crossover, but for about 30% of the cases it is higher.

These latter results imply that: (a) the electric fields commonly have a potential drop of 150–200 keV, (b) another process (possibly stochastic acceleration by waves generated in association with the particle dynamics) produces the electrons of $\gtrsim 200$ keV, and that this process requires a few seconds to operate, and (c) as bursts decay the electric field disappears and the electron distribution evolves to a simple power law, or one that breaks up because of the preferential loss of electrons of $E \lesssim 100$ keV, caused by collisions or by cyclotron maser radiation.

4. Multiwavelength Observations of Two Limb Flares

At the same time as the above research was being undertaken, we also began investigation of two limb flares observed during the First Max'91/SMM campaign in June 1989 (paper 5). This work complements that in the previous sections by providing additional information through the unprecedented coverage at multiple wavelengths. This data provides new details on the spectral and spatial evolution of the flares. The two flares being studied both occurred near the limb on June 20, 1989, and are being analyzed by graduate student Terry Kucera as part of her Ph.D. thesis research.

For the first flare at 14:57 UT, analysis of the VLA data shows a large ($\sim$3 arcmin) source extending off the limb. Hα imaging shows the appearance of a cool, dense loop whose position approximately coincides the radio emissions at 1.4 GHz during the early part of the flare. However, at later stages the radio emission appears to be coming from a different region, possibly a sympathetic flare. The radio spectra also indicate the evolution of the electron distribution from one which is dominated by gyrosynchrotron and plasma radiation to one which is dominated by bremsstrahlung as the loop fills with chromospheric material.

The second flare at 21:57 UT was observed in the radio by the VLA, OVRO, and RSTN. At 1.4 GHz it consists of three or four stationary, but time-varying sources, some polarized and others unpolarized which indicate that a number of magnetic loops are involved in the flare. The radio spectra contain evidence for plasma emission and multiple components of gyrosynchrotron emission.

Analysis is still proceeding, with emphasis currently being on comparing the Hα sources relative to the radio sources. This should provide additional information on the spatial distribution of accelerated electrons as well as the temporal evolution of the acceleration mechanisms.